Status of the X/S Source Catalog

David Gordon, Karine Le Bail

Abstract We summarize the current status of the X/S source catalog as preparations are being made for ICRF3 in 2018. The current X/S catalog has ∼20% more sources than ICRF2 and has considerably better and more homogeneous precision. Additional observations since 2009, including a second epoch VCS campaign, have resulted in precision improvements of ∼1.7 times for the ICRF2 non-VCS sources and ∼7 times for the ICRF2 VCS-only sources. But similar to ICRF2, the X/S catalog today is still relatively sparse and noisy in the south. Efforts are underway to provide a set of high precision, optically bright sources for alignment of the *Gaia* optical frame with ICRF3 in the coming years.

Keywords X/S catalog, ICRF2, ICRF3

1 Introduction

The second realization of the International Celestial Reference Frame (ICRF2) [1, 2] contained positions for 3,414 sources, obtained from X and S band dual-frequency geodetic and astrometric VLBI sessions. The sources in ICRF2 were divided into two groups because approximately 2/3 of them came exclusively from the six Very Long Baseline Array (VLBA) Calibrator Survey (VCS) campaigns [3, 4, 5, 6, 7, 8], had mostly been observed in only one VLBI session, and had average formal errors approximately five times larger than the other one-third. Of the 3,414 sources, 1,217 were classified as regular or 'non-VCS' sources, and 2,197 were classified as 'VCS-only' sources.

ICRF2 was a tremendous improvement over ICRF1. It used four times as much data (1.6 million vs. 6.5 million observations), contained 5.6 times as many sources (608 vs. 3,414), had a sixfold improvement in the noise floor (250 vs. 40 µarc-sec), and had twice better axis stability (20 vs. 10 µarc-sec). As we approach ICRF3 in 2018, we must realize that such huge gains are no longer possible. But ICRF3 will be significantly better in other ways.

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2 X/S Progress Since ICRF2

Since mid-2009, RDV VLBA sessions have been used to reduce the position uncertainties of ∼400 of the noisiest ICRF2 sources and to detect many new sources. Additional new sources have also been added in other IVS sessions, mostly in the southern hemisphere. Overall, as of March 2016, some 384 new sources have been added through the regular RDV and other IVS sessions since ICRF2.

In 2012, an IAU working group was formed to generate a third realization of the International Celestial Reference Frame by 2018. One of the goals for ICRF3 is to provide the highest accuracy reference frame possible for alignment of the *Gaia* optical reference frame with the radio reference frame. But in 2012, about two-thirds of the X/S sources were still single-epoch sources with much larger average position errors than the other 1/3. For the future alignment between the radio reference frame (ICRF3) and the optical (*Gaia*) reference frame, a more uniform precision in ICRF3 would be needed. Therefore, re-observing the single-epoch sources to improve their position errors became a high priority for ICRF3. In response, a small group was formed to request VLBA observing time to re-observe these sources in a second epoch VLBA Calibrator Survey Campaign (VCS-II).

The VCS-II campaign consisted of eight 24-hour VLBA sessions, run between January 2014 and March 2015. The recording rate was 2 Gbit/s, with 1.5 Gbit/s at X-band and 0.5 Gbit/s at S-band. By contrast, the original VCS1-6 sessions used only 128 Mbit/s for most of the sessions. Thus the VCS-II sessions were some 3–5 times more sensitive than the original VCS1-6 sessions. The VCS-II sessions observed 2,400 target sources, plus 182 ICRF2 defining sources for atmosphere calibration and alignment with ICRF2. Of these, 2,062 single-epoch sources were successfully re-observed, and their average inflated errors were reduced by a factor of 4.8. Also, 324 new sources were detected, all being sources that had been observed but not detected in the original VCS1-6 sessions. Only 14 sources were not detected. Results are reported in [9].

At the time of ICRF2, the two classes of sources had average inflated errors of .55/.81 milli-arc-second (mas) (non-VCS) and 2.11/3.56 mas (VCS-only) in RA/Dec. With all the new observations since ICRF2, the average inflated errors for the two groups are now .33/.45 mas (non-VCS) and .29/.50 mas (VCS-only). Being nearly the same, there is no longer any need for a two-class distinction between them. However, the new sources added since ICRF2 do have considerably larger average inflated errors, and so some distinction may still be necessary. There are currently 515 single-epoch sources in the X/S catalog, so a second class of sources would be a much smaller fraction in ICRF3 (less than 15%), compared to the large fraction ($\sim$2/3) in ICRF2. These new sources are generally very weak but there is hope of re-observing many of them before ICRF3.

3 The Current X/S Catalog

As of March 2016, there are 4,121 sources in the X/S catalog at GSFC, or $\sim$20% more than in ICRF2. Of these, 1,991 (48%) are the 'regular' or 'non-VCS' sources, i.e., sources that were **not** observed **only** in the VCS1-6 and/or VCS-II campaigns. The rest, 2,130 (52%), are 'VCS-only' sources, i.e., they were observed **only** in the VCS1-6 and/or VCS-II campaigns. Average inflated errors are actually smaller for the current VCS-only group compared to the current non-VCS group: 0.44/0.76 mas vs. 1.23/1.67 mas. However, the non-VCS group has a few single epoch sources that are very noisy and which skew the averages. Median inflated errors are similar for the two groups: 0.20/0.34 mas (current VCS-only) vs. 0.16/0.26 mas (current non-VCS).

Also, of the current 'non-VCS' sources, 784 were actually observed **only** in other VLBA sessions, mostly the RDVs. So in fact, 2,915 sources come exclusively from VLBA sessions, and only 1,207 were observed in non-VLBA sessions. This means that the VLBA has had a huge impact on the X/S catalog, accounting for 71% of the total number of sources.

4 Distribution of the X/S Sources

A deficiency in both ICRF1 and ICRF2 is that most of the sources were north of $\sim$–30° declination. Unfortunately this situation has not changed, and will not change, in ICRF3. The VLBI networks available in the southern hemisphere cannot approach the sensitivities of the VCS and VCS-II campaigns. There is some hope that an African network of large antennas will become available in a few years, but this would not be in time for ICRF3. Figure 1 shows the relative density of X/S sources in two degree declination strips. One can see that the density is fairly even in the +90° to –30° range, then drops to $\sim$1/3 as much in the –50° to –90° range. Source uncertainties are also very unevenly distributed between the north and the south. Figure 2 shows the distribution of inflated formal errors averaged in two degree declination strips. South of $\sim$–30°, the inflated errors increase dramatically and show much greater scatter.

5 Ongoing Work

Several efforts are currently underway to improve the upcoming ICRF3 and its usefulness to the scientific community. A group of 195 ICRF3–*Gaia* optically bright intercomparison sources are being observed regularly [10] to improve their positions and thus improve the alignment between ICRF3 and the *Gaia* optical

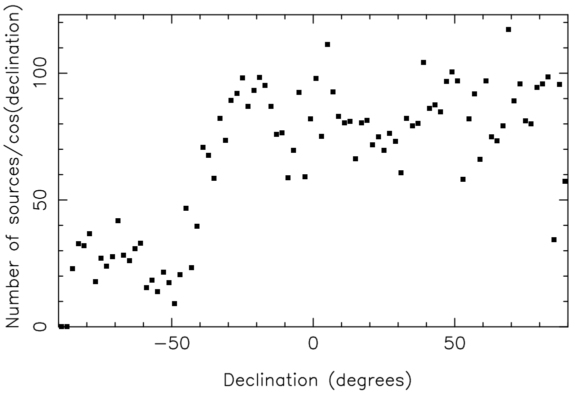

Fig. 1 Relative source density in 2° declination bins.

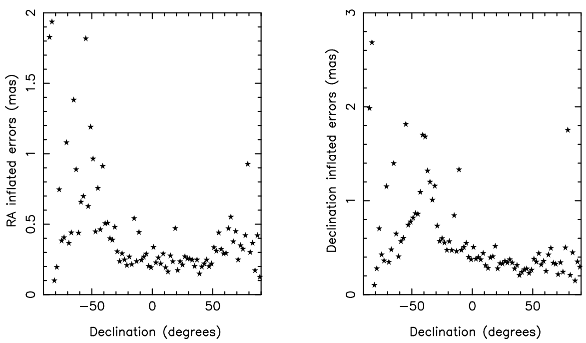

Fig. 2 Average inflated errors in 2° declination bins.

reference frame. Precision goals of 0.1 mas or better have already been obtained for most of them and will be obtained for all of them before ICRF3. Also, as of mid-2015, some 500 ICRF2 sources had not been re-observed since 2009 or earlier. These sources are now being added to the source monitoring program, and as of May 2016, 74 of them have already been re-observed.

6 Summary

ICRF3 will contain a large X/S catalog and maybe smaller catalogs at other radio frequencies (Ka/X and K bands). The X/S catalog will be at least 20% larger than in ICRF2, and the positions will be more precise and more homogeneous. There will also be no large second class of sources, as in ICRF2. Because of the increased precision, ICRF3 will also likely have a smaller noise floor than ICRF2. The current X/S catalog has more southern sources than ICRF2, but unfortunately the southern one-third of the sky will still be sparsely represented in ICRF3.

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